N65-81114

Code None

R-75

UNPUBLISHED PRELIMINARY DATA

SM-44/30

9 p.

LOCAL LET SPECTRA IN TISSUE FOR SOLAR FLARE PROTONS IN SPACE AND FOR NEUTRON PRODUCED RECOIL PROTONS*

Hermann J. Schaefer [1963] 13+p

U.S. Naval School of Aviation Medicine

Pensacola, Florida, USA

Fla.

6250002

(NASA CR-51651)

To be presented at the International Atomic Energy Agency Symposium on Biological Effects of Neutron Irradiations, Brookhaven, New York, 8 October 1963.

Experimental data on biological effects of proton radiations are available only for monoenergetic protons from accelerators and for recoil protons released in neutron radiation fields of various origin. These two types of proton beams differ basically with regard to their RBE. Protons in the multimillion e-volt energy range from accelerators have been shown by several investigators (1, 2) to have an RBE markedly smaller than one, whereas neutron produced recoil protons have an RBE considerably larger than one. In official regulations (3) a value of 10 is recommended for assessments of exposure from neutron recoil protons.

The discovery and analysis of solar proton beams in space have added a new type of proton radiation. The energy spectra of these solar protons as well as of those in the Van Allen Belt are wide continua of negative slope comprising the energy range from zero to many hundred million e-volts. Since biological experimentation with protons in space is quite costly and difficult, the question arises as to what extent a quantitative analysis of the energy spectra involved plus a comparison with those of neutron produced recoil protons and of high-energy monochromatic protons from accelerators would allow conclusions as to their RBE. The following discourse is an attempt at such a comparative evaluation.

Figure 1 shows the differential energy spectrum of a typical flare produced solar particle beam. As mentioned before, the spectrum shows consistently a pronounced negative slope; i.e., the particle flux decreases substantially toward higher energies. Figure 1 presents only the middle section of the spectrum, i.e., the section

(NASA Order R-75)

*The research reported in this paper was conducted under NASA Project Order No. R-75, National Aeronautics and Space Administration, Washington, D. C.

Opinions or conclusions contained in this paper are those of the author. They are not to be construed as necessarily reflecting the view or the endorsement of the Navy Department.

Presented at the Intern. Atomic Energy Agency Symp. on Biol. Effects of Neutron Irradiations, Brookhaven, N.Y., Oct. 8, 1963 which would predominantly contribute to the tissue ionization dosage in a human target under exposure conditions in space. For completeness sake, it might be said that toward the right the spectrum continues its negative slope until it has dropped to the level of the proton component of the ordinary cosmic ray beam. Toward the left, the particle flux continues in the same way with ever-increasing flux values to the geomagnetic or instrument cutoff below which direct measurements are no longer possible. Indirect evidence from auroral phenomena associated with flares indicates that the energy spectrum extends all the way down to thermodynamic particle velocities reaching enormous flux values.

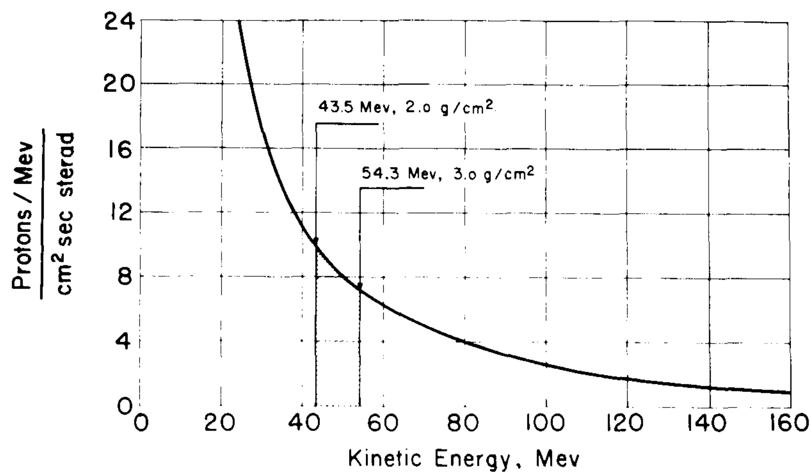

Figure 1

Differential Energy Spectrum of Typical Solar Proton Beam

If a proton radiation of the spectral type shown in Figure 1 enters absorbing material, a transition of the energy spectrum sets in, resulting in continuous profound changes of the spectral configuration. If we single out, in the spectrum of Figure 1, a narrow interval, e.g., from 43.5 to 54.3 Mev corresponding to a range interval in tissue from 2.0 to 3.0 g/cm^2, it is seen that, because of their slightly higher LET, the particles of lower energy in this interval will lose energy faster in a given thickness of absorbing material than those of higher energy at the upper end of the energy interval in question. The original energy spread of 54.3 minus 43.5 equals 10.8 Mev, therefore, must become larger as the radiation penetrates more deeply into the absorber. Since no new particles are generated, the particle number per Mev must decrease. The degradation of the selected energy interval in the incident beam due to this effect is shown for consecutive steps of 0.4 g/cm^2 in Figure 2. As the particle flux spreads over larger intervals the spectral slope decreases continuously, becomes horizontal, and finally reverses. At the same time the differential particle number drops continuously. It does so in an uneven fashion with the lower end of the energy interval affected most. In our particular case, the particle number drops from 9.75 protons/Mev at 43.5 Mev to 0.20 protons/Mev at

0 Mev. The cause of this continuous transition lies in the strongly nonlinear range/energy relationship. It has the important consequence that an incident spectrum of monotonic negative slope undergoes a basic change in its configuration, developing a pronounced maximum at a finite energy. It is seen, then, that in comparing space radiation proton spectra with spectra of recoil protons released in tissue by neutrons, one has to investigate the local spectra, i.e., the spectra as they develop in tissue at the point of interest.

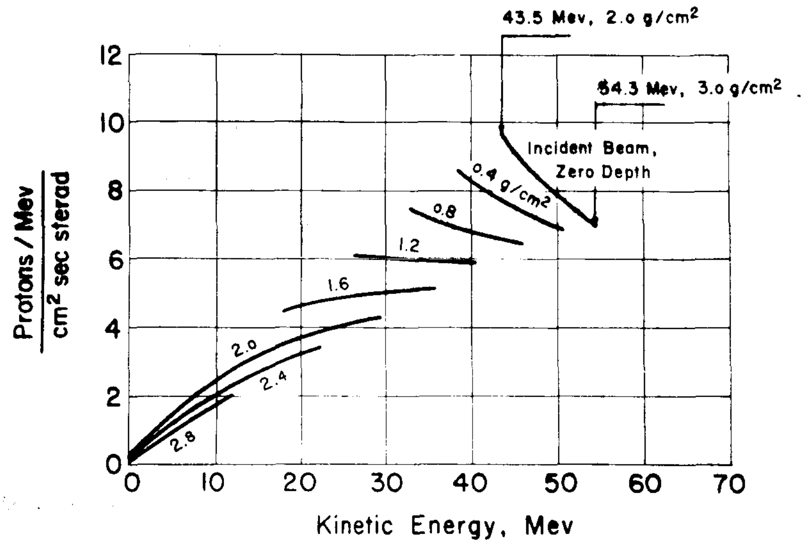

Figure 2

Spectral Degradation of Small Interval of Energy Spectrum in Absorbing Material

The upper graph in Figure 3 shows the differential energy spectrum for recoil protons released in organic material by so-called Watt Spectrum neutrons (4). It is a continuous spectrum with a pronounced maximum at a kinetic energy slightly below 0.5 Mev. The lower graph shows the flare produced proton spectrum of Figures 1 and 2 in the interval from 0 to 200 Mev energy after the beam has travelled through 2 g/cm^2 of organic material. Except for a factor of 50 in the abscissa scale the two spectra show the same basic configuration. Actually, of course, this similarity is only superficial. Radiobiologically, the two spectra represent basically different radiations because the maxima occur at energies for which the LET is greatly different. Therefore, the rem/rad ratio of the bulk of the ionization dosages will be greatly different. This particular aspect is described in Figure 4. It shows the initial sections of the spectra from 0 to 1.6 Mev kinetic energy, in which the LET passes through the Bragg peak, in higher resolution. In addition to the differential particle numbers of the two spectra the LET is shown over the same abscissa scale. It is evident from Figure 4 that, for Watt Spectrum protons, the bulk of the particle flux centers around high LET values whereas the flare spectrum carries only a few per cent of its total flux in that particular LET region.

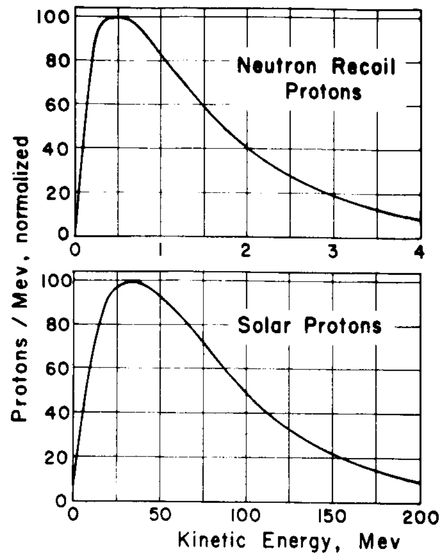

Figure 3

Differential Energy Spectrum of Neutron Recoil and Solar Protons

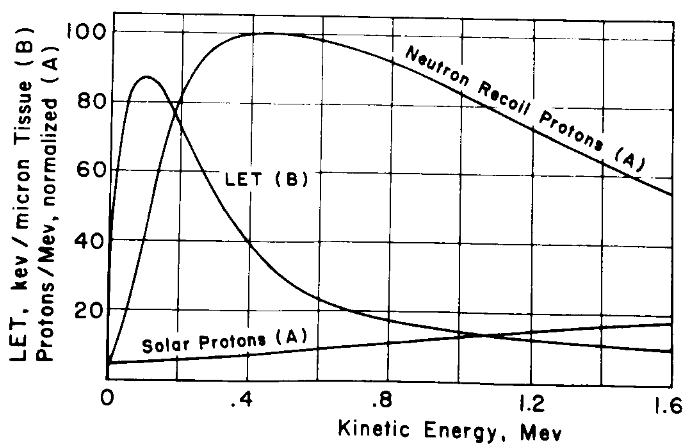

Figure 4

Initial Sections of Neutron Recoil and Solar Proton Spectrum
Aligned with LET

For a more precise definition of the basic dissimilarity of the two spectra, evaluation of the LET spectra, i.e., determination of the fractional energies or doses produced at particular LET values for the entire LET range of protons, seems the appropriate method. If such an analysis is to furnish a true picture of the local LET/energy distribution in the micro-structure of living tissue, those secondary electrons which receive enough energy to branch out from the path of the parent proton have to be considered as separate particles and their LET/energy distributions have to be analyzed separately. These aspects have been discussed by Spencer and Fano (5), Spencer and Attix (6), Burch (7), Cormack and Johns (8), Rossi (9), Howard-Flanders (10), and Bruce, Pearson, and Freedhoff (11). It has become generally accepted in this type of LET study to define as local energy dissipation any transfer in which an energy of 100 e-volts or less is exchanged.

A problematic issue in establishing the local LET spectrum is the track length along which a given LET value is maintained. Figure 5 explains this in more detail. It shows the local LET for electrons and protons as a function of residual range. Selecting an LET value of, e.g., 25 kev/micron tissue, one sees that an electron reaches this value only at the very end of its track and maintains it only for about 15 millimicra. A proton, on the other hand, reaches this value much earlier in terms of residual track length and accordingly maintains it over a much longer distance. If we assume, for instance, that a submicroscopic sensitive target volume in a living cell has a diameter of 50 millimicra and will require, in order to be destroyed or deactivated, central traversal by an ionizing particle of 25 kev/micron T, we readily see that an electron of 25 kev/micron T cannot fulfill this requirement, whereas one proton will provide ample track length even for several such traversals. These relationships constitute the basic problem of the target theory and have been investigated both theoretically and experimentally by many investigators (12).

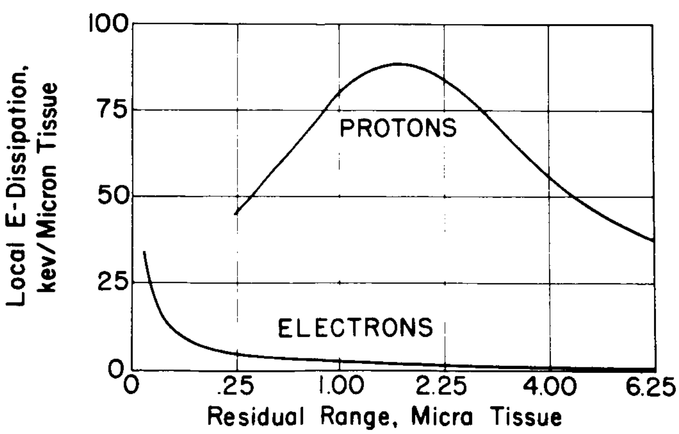

Figure 5

Local Energy Dissipation of Electrons and Protons in Terminal Section of Track in Tissue

It is seen from Figure 5 that quite generally a proton maintains, over at least 6 micra of its residual range in tissue, a local energy dissipation in excess of the maximum which an electron can ever reach. This, then, would constitute a basic difference between electrons and protons quite aside from the just mentioned criterion that protons maintain a certain LET over a longer track length. These relationships show how problematic it actually is to compare the energy dissipation by electrons to that of protons. To find a method for a quantitative description of the microscopic and submicroscopic distribution of the ionization events in tissue for the two types of particles, which would allow a true comparison down to all details, seems a very difficult task, particularly in view of the fact that present knowledge on the energy transfer mechanisms in the range of low and very low energies is fragmentary in many instances. Yet whatever the details of these mechanisms might be, one can be certain that the high RBE of low energy protons specifically rests on the very high LET values in the terminal sections of their tracks and that the energy dissipation at these high LET values is produced exclusively by soft collisions of the proton itself. Secondary electrons do not contribute to this part of the ionization dosage for the obvious reason that the LET of an electron never exceeds 30 kev/micron. In a comparative evaluation of LET spectra of protons, therefore, the analysis can be limited to the contributions from soft collisions of the protons themselves. This method is followed throughout the following discussion.

Figure 6 shows three different LET spectra. The one at the top pertains to 220 kv standard x-rays as communicated by Cormack and Johns (8). Since the mechanism of energy dissipation for low energies is not well known, Cormack and Johns have lumped together the entire energy dissipated at LET values beyond 1 kev/micron T and indicated it in the graph merely as a block of correct total area. The horizontal upper contour of this block does not in any way indicate the actual configuration of the LET spectrum. The center graph of Figure 6 pertains to solar protons after they have travelled through 2 g/cm^2 of organic material, in other words, to the energy spectrum shown in the lower graph of Figure 3. It is interesting to see that the bulk of the energy dissipation of both radiations, 220 kv standard x-rays as well as solar protons, takes place with almost identical LET spectra. Merely a very small fraction of the solar proton spectrum extends into the LET range beyond 30 kev/micron T. This section has no counterpart in the x-ray spectrum. The bottom graph of Figure 6 shows the LET spectrum of neutron recoil protons, i.e., of the energy spectrum shown in the upper graph of Figure 3. Contrary to the flare spectrum (center graph of Figure 6) the bulk of the energy dissipation has shifted into the region of high and very high LET values. The center and bottom graphs of Figure 6 express, in exact quantitative terms, the basic difference between solar protons in space and neutron recoil protons.

It seems of interest to investigate whether the close similarity between the LET spectra of x-rays and solar protons remains preserved if the proton beam penetrates more deeply into the absorber. Figure 7 conveys some information on this question. It shows the changes which occur in the LET spectrum of a solar proton beam as it penetrates from 2 to 8 g/cm^2 depth of organic material. For better resolution the right end of the graph covering the LET values from 30 to 100 kev/micron T has been set off and drawn at a larger scale. Inspection of the left-hand part shows that the configuration of the spectrum changes comparatively little. As a general estimate, therefore, it would not seem that either of the

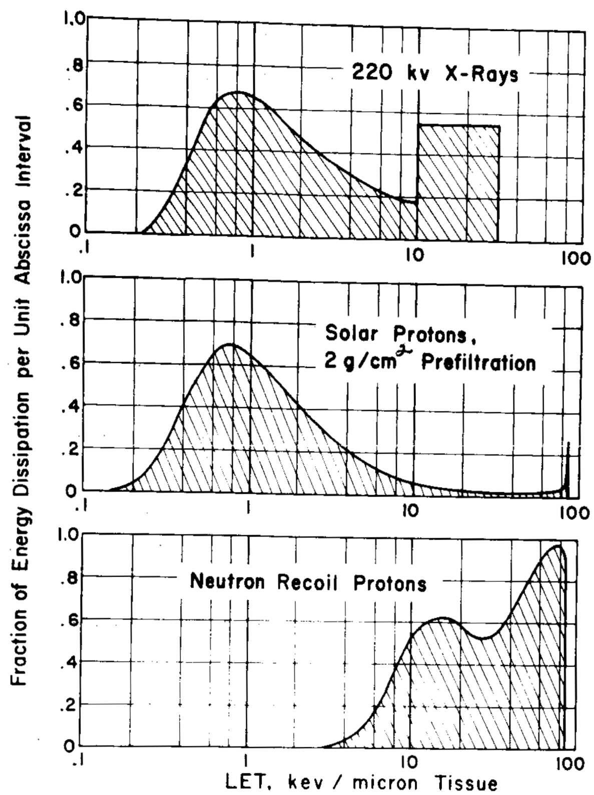

Figure 6

LET Spectra of X Rays and of Solar and Neutron Recoil Protons

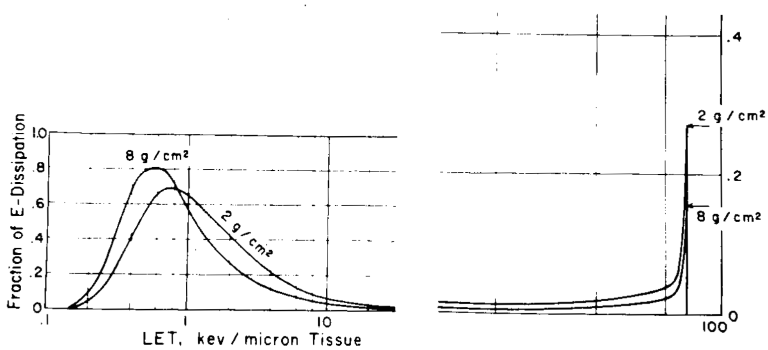

Figure 7

LET Spectra of Solar Protons at Two Different Depths in Tissue two spectra, the one for 2 g/cm^2 or for 8 g/cm^2 depth, differs significantly from the LET spectrum of 220 kv standard x-rays. The situation is different for the high LET fraction. As seen from the right-hand graph in Figure 7, a marked decrease of the fractional ionization dosage occurs as the beam progresses from 2 to 8 g/cm^2 depth. This is due to the fact that protons of lower energies are attenuated earlier as the beam travels through absorbing material. It should be remembered that the total areas under the curves in Figures 7 are equal. That means they hold for equal total energy dissipation, i.e., for equal rad doses, at 2 g/cm^2 and at 8 g/cm^2 depth. For a given beam in an actual case, the rad dose at 8 g/cm^2 depth would of course be substantially smaller than at 2 g/cm^2.

The foregoing analysis has been carried out strictly on the level of physical dosimetry without introducing, at any phase of the evaluation, the problematic issue of the RBE. Fractional areas in the graphs of Figure 6 directly represent fractions of ionization doses. If one wants to proceed from rad to rem doses, appropriate RBE factors would have to be applied to corresponding areas under the curves. It is not intended to discuss these particular aspects further. One should realize, however, that, quite aside from the problem of selecting special RBE factors in a given case, the right-hand side of the LET spectrum in Figure 7 represents a radiation quality basically different from the main part of the spectrum. A radiobiologically correct and complete dosimetry of a solar particle beam, then, would seem to require separate determination of the two fractions of the ionization dosage. Of these, the high and broad maximum at the left up to about 10 kev/micron T could be considered, for all purposes of assessment of exposure, as essentially equivalent to an x-ray exposure, whereas the right-hand section would have to be considered as essentially equivalent to neutron exposure. Since experimental evidence with test animals indicates that damage from high LET radiation, especially for low-dose rate long-term exposure, shows a smaller recovery effect than damage from x or gamma rays, separate determination of the two dose fractions seems especially advisable if assessments of exposure status over longer time intervals are involved. For a one-time exposure, on the other hand, it might be acceptable to dispense with such separate measurements in view of the smallness of the high LET fraction as compared to the total dose.

In view of the basically different quality of the two dose fractions under discussion, it seems of special interest to define the components of the local differential energy spectrum producing them. It is seen from Figure 4 that the peak at the upper end of the LET spectrum is produced by protons passing through the Bragg peak of their ionization curve, i.e., by terminating protons. Visualizing a thin layer of tissue of 10 micra thickness, for example, traversed by a solar proton beam, one sees, then, that the particles ending in this layer produce the high LET dose, whereas the bulk of the particles of higher energy passing through contributes the main part of the total ionization in the LET spectrum. The so-called "enders," i.e., protons coming to rest in a given differential volume element of an irradiated object, are also of special interest for the physicist, particularly in emulsion work, because their local density allows direct inferences on the special configuration of the incident beam. These relationships have been discussed from the standpoint of the cosmic ray physicist by Ney and Stein (13).

Within the framework of the present discussion it can be summarized that a complete dosimetric analysis of a solar particle beam as well as of any heterogeneous proton beam from an outer source would require measurement of the total ionization at the given point of interest in tissue and a separate determination of the number of "enders" per unit volume at the same point. Construction of an instrument which would accomplish this task efficiently should pose an interesting challenge for the designer.

REFERENCES

1 WANG, C. C., LAWRENCE, J. H., and TOBIAS, C. A., in Biology and Medicine Semi-Annual Report UCRL-10211 (LAWRENCE, J. H.) University of Calif., Radiation Lab., Berkeley, Calif. (1962).

2 KURLYANDSKAYA, E. B., in Problemy kosmicheskoy biologii 2 (SISAKYAN, N. M. and YAZDOVSKIY, V. I.) USSR Academy of Sciences (1962) 354-358.

3 In Atomic Energy, Federal Regulations, Title 10, Chap. 1, Part 20. Atomic Energy Commission, Washington, D. C. (1958).

4 KRONENBERG, S. and MURPHY, H. M., Jr., Radiation Res. 12 (1960) 728-735.

5 SPENCER, L. V. and FANO, U., Phys. Rev. 93 (1954) 1172-1181.

6 SPENCER, L. V. and ATTIX, F. H., Radiation Res. 3 (1955) 239-254.

7 BURCH, P.R. J., Radiation Res. 6 (1957) 289-301.

8 CORMACK, D. V. and JOHNS, H. E., Brit. J. Radiol. 25 (1952) 369-381.

9 ROSSI, H. H., Radiation Res. 10 (1959) 522-531.

10 HOWARD-FLANDERS, P., in Advances in Biological and Medical Physics 6 (TOBIAS, C. A. and LAWRENCE, J. H.) Academic Press, Inc., New York (1958) 553-603.

11 BRUCE, W. R., PEARSON, M. L., and FREEDHOFF, H. S., Radiation Res. 19 (1963) 606-620.

12 HUTCHINSON, F., Science 134 (1961) 533-538.

13 NEY, E. P. and STEIN, W. A., J. Geophys. Res. 67 (1962) 2087-2105.